Identification of solar wind stream interfaces: A comparison of Ulysses plasma and composition measurements

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Abstract

Measurements of the specific entropy argument of solar wind protons, $T/n^{\gamma-1}$ reveal that nearly every occurrence of a high-speed stream seen at Ulysses in 1992-3 is characterized by an abrupt interface at its trailing edge. There is a discontinuous drop in specific entropy at the interface from a high value in the high-speed wind to a lower value in the slow interstream wind. This interface is coincident with, but much more abrupt than, compositional changes measured by the SWICS instrument [*Geiss et al.*, 1995]. These results suggest that a relatively thin interface can be identified in the plasma data which separates two plasmas of distinctly different origins as determined by the compositional measurements. A superposed epoch analysis performed on seventeen interfaces reveals 1) the drop in entropy is due to an enhancement in density along with a gradually declining temperature profile on the trailing edge of the stream 2) the interface is characterized by a distinct drop in the alpha/proton ratio from a value of ~5% typical of the fast wind to ~4% characteristic of the slow solar wind 3) relative changes in Mg^{10}/O^{6} at the interface are as large as the variations in the total Mg/O ratio and the O^{7+}/O^{6+} freezing-in temperature. This combination of commonly measured solar wind parameters into an easily calculated quantity gives a strong signature of the interface which is preserved as far out in the heliosphere as 5 AU. The specific entropy argument is also used to identify the interface at the leading edge of these same solar wind streams. It is found that the largest jump in entropy that we have identified as the interface is often not coincident with the interface identified in a previous study by *Wimmer-Schweingruber et al.* [1997].

Introduction

In early 1992, at 13° S latitude, in transit to the southern solar pole, Ulysses began to sample a recurrent high-speed solar wind stream which emanated from a coronal hole at the south pole of the Sun. This recurrent stream was seen regularly each solar rotation until the spacecraft was continuously immersed in high-speed solar wind by 36°S latitude. *Bame et al.* [1993] provides a detailed summary of these observations. During this time the SWICS (Solar Wind Ion Composition Instrument) onboard Ulysses made continuous composition and temperature measurements of all major solar wind ions [*Gloeckler et al.*, 1992]. Patterns in the variations of the Mg/O ratio and the O^{7+}/O^{6+} freezing-in temperature were found to be virtually identical to each other and anti-correlated with the solar wind velocity. Further, an abrupt transition from high to low values of these parameters was observed at both the leading and trailing edges of the stream. A superposed epoch analysis of these data is reproduced in Figure 1 [*Geiss et al.*, 1995]. Those observations are significant since they suggest that the chromosphere and corona have a common, sharp boundary separating the low- from the high-FIP (first ionization potential) region in the chromosphere and the low- from the high-temperature region in the corona.

In a study of solar wind streams, *Siscoe and Intriligator* [1993] found the specific entropy of the ions, which is proportional to $\ln(T_i/n^{\gamma-1})$, and which should be a constant of the flow, to be enhanced in the high-speed stream and further that an abrupt increase is a good indicator of the stream interface. ($T_i/n^{\gamma-1}$ is referred to as the specific entropy argument.) In this study, the specific entropy argument is compared with the O^{7+}/O^{6+} freezing-in temperature previously reported by *Geiss et al.*, [1995] and Mg^{10}/O^{6} ratio. A close anti-correlation is found including a discontinuous change in entropy coincident with both the leading and the trailing edge of the high-speed stream identified in the SWICS data.

Although it has been shown that the trailing edges of high-speed streams, when mapped back to the Sun, originate within a narrow range of solar longitudes corresponding to the boundary of the coronal hole from which the stream emanates [*Nolte et al.*, 1976], no specific feature has been previously identified as the interface at the trailing edge. We identify this discontinuous change in entropy as a marker of the trailing edge interface. These observations suggest a new useful combination of solar wind parameters that can serve as an identifier of the stream interface at both the leading and trailing edge of a high-speed solar wind flow in the absence of data of the type the SWICS instrument provides.

Analysis

Ulysses plasma and magnetic field data from mid-June, 1992 through mid-July, 1993 were used for this study. During this time Ulysses sampled the recurrent solar wind stream more than 15 times. One hour averages were used to identify the interface and subsequently higher time resolution data were used to examine the interfaces in detail. The specific entropy argument, $T/n^{\gamma-1}$ was calculated for the solar wind protons using a value of γ=1.5. (This is close to the value of $\gamma = 1.46$ derived empirically in a study of free-streaming solar wind measured at Helios 1 [*Totten and Freeman, 1995*]). The specific entropy then reduces to $T/n^{1/2}$, with T in K and n in cm^{-3}.

Figure 2 shows various solar wind parameters along with the SWICS compositional measurements. In the top panel the solar wind alpha particle velocity (V_α , dashed line) measured by SWICS along with the corresponding oxygen freezing-in temperature (T_o , solid line) are shown. Note that T_o is plotted on a logarithmic scale and in an inverse sense to emphasize correlations with the solar wind velocity. The proton entropy, density and temperature, the magnetic field strength and the total pressure (magnetic plus thermal) are shown in the subsequent panels. The entropy is clearly enhanced in the high-speed stream (shaded) and a discontinuous jump occurs at both the leading and trailing edges. The vertical lines indicate the leading and trailing interfaces as identified by visual inspection of the hour averages. [The interfaces are most easily identifiable at the 1-hour time resolution]. For all but stream 8 an abrupt interface was identified at the trailing edge. Although there is no remarkable change in any individual solar wind parameter that would lead one to identify it as a boundary, the entropy gives a strong signature. Coincident with this jump in entropy but occurring over a longer time period is a change in the oxygen freezing-in temperature, T_o measured by SWICS. The time resolution of the composition measurements is typically 3 hours or more. Variations in Mg/O have been shown to be virtually identical to each other but are not shown here.

The events identified as trailing edge interfaces are shown in table 1. Once the interface was identified in the hour averages, higher resolution plasma data (sampled in intervals of either 4 or 8 minutes) were used to determine the duration of the interface and subsequently to infer its thickness. A stack plot of this parameter at high time resolution is shown in figure 3 for eight of the streams included in this study. Although the entropy is generally declining throughout the trailing edge, the interface is characterized by a distinct discontinuous drop. The start and stop times of the interfaces and their durations, are tabulated in Table 1. The average duration is 43 minutes and the most abrupt interface occurs in only 8 minutes, which suggest a boundary thickness of roughly 10^5 kilometers. Shown in columns 8-10 are the minimum and maximum speed on either side of the interface and the speed at the interface. The minimum speed is the lowest value occurring in the trough of the slow solar wind following the interface and the maximum is the highest speed of the crest preceding it. Typically the interface occurs during the declining portion of the speed profile when the speed is low. Just as the interface at the leading edge occurs at the pressure ridge, the trailing interface occurs approximately when the total pressure, thermal plus magnetic, has reached a minimum. [This is more readily apparent in the superposed epoch analysis that follows.]

Superposed epoch analysis -

A superposed epoch analysis of the specific entropy argument and other relevant solar wind parameters was performed at all the trailing interfaces to emphasize the characteristic changes associated with the interface. Hour averages of the plasma data were used for this analysis which extends 8 hours either side of the interface. The data are keyed on the abrupt drop in specific entropy observed in the hour averages. Error bars indicate estimates of the error of the mean ($\sigma_d/N^{1/2}$), where σ_d is the standard deviation and N is the number of events contributing to the average. Figure 3 shows the results of the superposed epoch analysis for specific entropy (top panel) and various other solar wind parameters. As the figure shows, specific entropy decreases roughly by a factor of one third at the interface. This decrease can be accounted for by a jump in density (panel 2) as the temperature (panel 3) gradually decreases on the trailing edge of the stream. Since hour averages are used, the abruptness of the interface which is apparent in the high resolution data is not accentuated here. A distinct drop in the alpha/proton ratio (panel 4) occurs across the boundary from a value of ~5% typical of the fast wind to ~4% more characteristic of the slow solar wind. This well-known change was first reported by *Gosling et al.,* [1978] in their study of leading edge interfaces and in fact it is this difference that caused him to suggest that two types of unmixed plasma exist. The total pressure is plotted in the next panel. (Error bars are omitted from this panel since they are quite large and expanding the vertical axis to encompass them obscured the pressure variations.) In the bottom panel the Mg^{10}/O^{6} ratio from the SWICS instrument is plotted. This parameter was used instead of total complement of Mg and O since it is readily available for the entire interval of this study at the National Space Science Data Center Archive. The typical sampling rate of the instrument is 3.5 hours and an average is calculated each hour, therefore not all the cases contribute to the average value for that data point. The results are consistent with the jump in total Mg/O shown in figure 1 and also show that the Mg^{10}/O^{6} ratio gives a strong signature of the interface.

The results of the superposed epoch analysis for the alpha-proton speed difference, $V_{\alpha p} = \left|\vec{V}_\alpha - \vec{V}_p\right|$ are shown separately for an extended interval in Figure 4. $\vec{V}_\alpha$ and $\vec{V}_p$ are the vector velocities of the alpha particles and the protons, respectively. The results are shown for two days prior to and one day following the trailing interface. In contrast to the superposed epoch analysis of *Gosling et al.*, [1978] which revealed a substantial (~20 km/s) jump at the leading edge, no abrupt change occurs across the trailing interface. The decline of $V_{\alpha p}$ with declining solar wind speed along the trailing edge is consistent with the previously documented correlation between V_p and $V_{\alpha p}$ [c.f., Neugebauer, 1996]. $V_{\alpha p}$ has reached its low interstream value some ten hours prior to the trailing edge interface. Although the alpha particle fraction changes abruptly at the interfaces, the alpha flow speed relative to the protons does not.

Identification and analysis of magnetic field discontinuities near the trailing interface-

Magnetic field data throughout the duration of the interface were searched for major discontinuities. One would expect to identify a tangential discontinuity at the interface separating two plasmas of distinct origins. Typically discontinuities could be found within the interval defined as the interface but they were unremarkable in comparison to other discontinuities nearby. These discontinuities were analyzed further in order to classify them as tangential or rotational. To do this, the criteria of *Neugebauer and Alexander* [1991] were used. In that study a discontinuity was classified as tangential if the ratio of intermediate to minimum eigenvalues determined from minimum variance analysis, $\lambda 2/\lambda 3 > 2$, $\Delta B/|B| < 0.2$, (where ΔB is the change in field magnitude across the discontinuity and $|B|$ is the larger of the fields on either side), $B_n < 1$ nT and $B_n > 2\sigma_n$, where B_n is the normal component of the field across the discontinuity and σ_n is the error in B_n. Half the discontinuities examined could be immediately classified as tangential. Although none of the remaining discontinuities had a large normal component, their classification was inconclusive primarily because the normal component of the field determined from minimum variance analysis was somewhat larger than twice the error, $2\sigma_n$. No further analysis was performed.

Identification of leading edge interfaces- As has been done in previous studies [c.f. *Intriligator and Siscoe*, 1994], entropy is used in this study to identify the interface at the leading edge of these streams. These identifications are shown in Table 2. The largest entropy signature at the leading edge interface is often not the interface identified in a previous study of these same streams by *Wimmer-Schweingruber et al.* [1997]. In that study, stream interfaces were also identified using plasma parameters measured by the SWOOPS instrument and by an abrupt increase in kinetic temperature, accompanied by a simultaneous decrease in density (both by a factor larger than 2). These times are also listed in the table. Figure 5 shows examples of two streams for which a discrepancy exists. The solar wind speed and specific entropy argument are shown in the top panels and the corresponding proton density and temperatures are shown in the bottom panels. The interface identified by the largest jump in entropy is indicated by the solid line and the interface identified by WS is indicated by the dashed line. These discrepancies are presented to emphasize the usefulness of entropy as a marker of the interface.

Discussion

Identification of the eastern trailing edge of a solar wind stream is useful in mapping back features to the solar surface since it suffers less distortion with propagation from the Sun. Because the region is rarefied, the plasma is less affected by acceleration, deceleration and shock formation. Previous studies, in which large-scale velocity structure has been mapped back to the corona, have demonstrated excellent agreement of the mapped velocities in the rarefaction regions with coronal hole boundaries both at 1 AU [*Nolte et al.*, 1976] and as far out as 5 AU [*Mitchell et al.,* 1981]. In this study we have identified an easily calculated quantity which is a marker of a well-defined interface within this rarefaction region. Its coincidence with changes in composition, Mg/O, Mg^{10}/O^{6}, and alpha/proton ratio, and oxygen freezing-in temperature indicates it separates two plasma of distinct origins.

Although SWICS compositional measurements give a strong indication of the stream interface, the SWOOPS plasma measurements have the distinct advantage of higher time resolution. The SWOOPS plasma instrument has a sampling rate of 4 or 8 minutes whereas, the oxygen and carbon freezing-in temperatures require an accumulation of one hour's worth of data to achieve satisfactory statistics. In the case of Mg/O ratio, 16 instrument cycles are required, resulting in approximately 3.5 hours time resolution. In a previous study of stream interfaces, *Wimmer-Schweingruber et al.* [1997], suggest that the composition of the plasma (freezing-in temperature) is better preserved than its kinetic properties, therefore the SWICS composition measurements have an advantage. Although density and kinetic temperatures have been influenced by the interaction region, we demonstrate here that a strong signature of an interface is equally well-preserved in the plasma parameters out to 5 AU. They further suggest that multiple interfaces observed at some of these streams are not identifiable in the plasma data alone, however, as table 2 indicates, multiple interfaces can in fact be identified using plasma parameters alone. The simple advantage of using the specific entropy argument in identification of the interface is the relative sampling rates of the instruments.

The applicability of the polytropic relation, p/ρ^{α} = constant has been demonstrated in various analyses of space plasmas. Studies by Feldman, [1978], Sittler and Scudder [1980], Osherovich, [1993], Totten et al., [1995], Newbury et al., [1997] are some examples. The typical approach is to determine if the polytropic approximation is valid (by fitting it to the data of interest) and to quantitatively evaluate the polytropic index. As pointed out by Siscoe [1983], the quantity which is constant in this expression is related to the specific entropy argument, since the entropy can be expressed as $\ln(T/n^{\gamma-1})$ (with a polytropic index $\alpha = \gamma$ for an adiabatic or isentropic process). Further, it can be shown that this parameter is constant only on a given streamline. In a study using Helios data, Totten et al. [1995] evaluated the polytropic relation for solar wind protons. The polytropic index, α was found to be independent of speed state and had an average value of 1.46 $\pm$0.04. The quantity which should be constant in the polytropic relation p/ρ^{α}, was evaluated and found to depend on speed state but not on radial distance for the two distances examined, 0.3 AU and 1.0 AU. In a study of Ulysses high latitude solar wind measurements, Goldstein et al., [1996] examined expressions of the functional form $V = AT/(n^s r^t)$ where the power laws indices s and t were chosen to obtain the best fit to V. They found that $T/n^{1/2}$, which is simply the specific entropy argument with a choice of $\gamma = 1.5$ was best predicted by the velocity in both Northern and Southern hemispheres. These two studies validate the choice of $\gamma = 1.5$ for the solar wind and suggest the notion of specific entropy as a streamline constant too is valid.

The thickness of the solar wind stream interface has implications regarding its origin. Burlaga [1974], proposed that the interface developed in interplanetary space as a consequence of nonlinear stream evolution, generated by a temperature difference in the corona. The interface Burlaga envisioned was roughly 10^6 km thick at the leading edge of the stream. Gosling [1978] viewed the structure as a sharper interface which is likely to have formed back at the Sun and not in interplanetary space. In that study the interfaces occurred over a very short duration (shorter than the sampling time of the instrument) corresponding to a structure on the order of 10^4 km in width. The thickness of the interface at the trailing edge as determined in this study is some where between these two extremes. However the trailing interface is located in the rarefaction region, which is expanding with distance from the Sun and is likely to be thicker than the interface at the leading edge where compressive effects are likely to influence the thickness of the structure.

Conclusions

The specific entropy argument has proved useful in identification of the interface at the trailing edge of a recurrent solar wind stream observed at 5 AU by the Ulysses spacecraft. For almost every occurrence of this stream at the spacecraft an interface separating high entropy, fast solar wind flow from slower interstream wind could easily be identified. A distinct drop in the alpha/proton ratio occurs across the boundary from values typical of the fast wind to those more characteristic of the slow solar wind. The interface coincides with but is more abrupt than changes observed in the total Mg/O ratio and the O^{7+}/O^{6+} freezing-in temperature. Relative changes in Mg^{10}/O^{6} also give a strong signature of the interface.

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Figure Captions

Figure 1. Superposed epoch analysis of T_o, the O^{7+}/O^{6+} freezing-in temperature, the Mg/O ratio and the solar wind speed represented by the alpha particle speed measured by SWICS from *Geiss,* [1995].

Figure 2. Overview plot of data used in this study. The top panel shows the oxygen freezing-in temperature (solid line) and solar wind velocity (as determined from the alpha velocity measured by the SWICS instrument). Hour averages of the specific entropy argument as defined in the text is shown in the next panel (units 10^{-4} ° K/cm $^{3/2}$). Also shown are hour averages of the proton density, temperature, magnetic field magnitude and total (thermal plus magnetic) pressure. The high speed streams are numbered and shaded.

Figure 3. Stack plot showing proton specific entropy argument at high time resolution at the trailing interface for eight of the streams examined in this study. The stream number is noted in the upper right corner of each panel. Each tic on the horizontal axis denotes one hour. The interface is marked by a vertical dashed line.

Figure 4. Results of a superposed epoch analysis for 8 hours either side of the trailing edge interface. The specific entropy, proton density and temperature, alpha:proton ratio, total pressure and Mg ^{10}/O^{6} ratio are shown.

Figure 5. Superposed epoch analysis for the alpha proton velocity difference over an extended interval, 2 days prior to and one and a half days following the trailing interface.

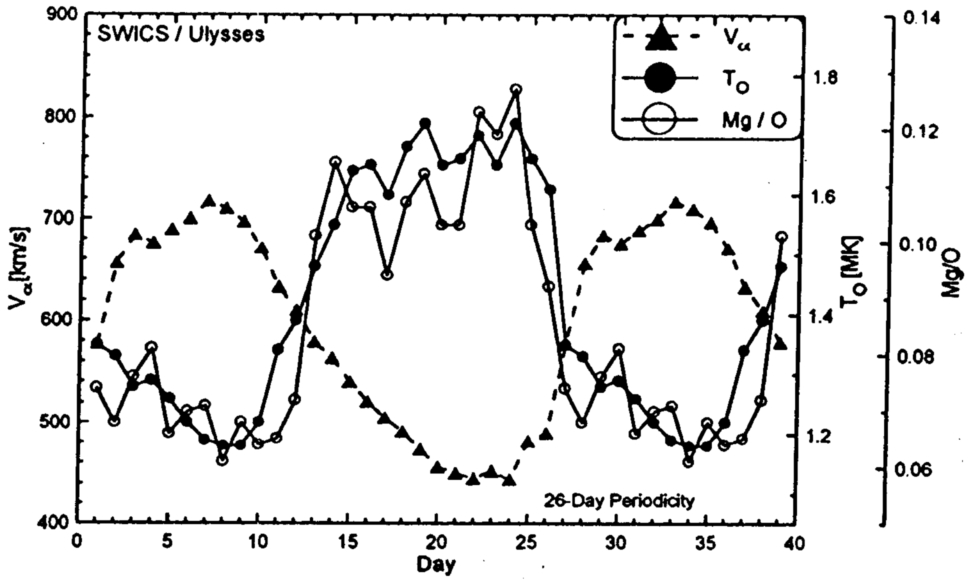
Figure 6. Two examples of leading edge interfaces in which discrepancies exist between the identifications of Wimmer-Schweingruber and those marked by the largest jump in specific entropy argument. The WS identification is marked by a dashed line and the entropy interface is marked with a solid line. The corresponding density and temperature profiles are shown in the bottom panels.

Stream #	Duration (minutes)	Start Time			Stop Time		V_{max}	V_{min}	V_{int}	Comments
		Year	DOY	hr:min:sec	DOY	hr:min:sec				
1	32	1992	193	23:10:27	193	23:42:35	615	404	485	
2	-		219		219		729	423	525	Plasma data gap from 219 06:57:15 - 17:52:49
3	8		245	17:36:44	245	17:48:46	788	423	491	
4	8		272	16:30:02	272	16:38:06	820	428	477	
5	36		298	09:24:28	298	10:00:37	771	400	483	
6	24		322	15:17:04	322	15:40:58	988	434	568	CME from day 319 09:45 to day 320 22:50
7	40		346	23:11:55	346	23:51:39	749	377	551	
8	-		-	-	-	-				
9	32	1993	41	13:51:45	41	14:23:27	780	435	464	boundary not distinct
10	29		64	01:51:15	64	02:19:23	753	398	547	
11	16		92	18:30:47	92	18:46:51	805	427	488	
12	8		121	03:36:37	121	03:44:56	805	549	571	
13	56		139	20:31:43	139	21:27:11	828	557	671	
14	63		164	02:35:01	164	03:38:31	858	541	684	
15	24		195	15:25:18	195	15:49:00	812	546	686	
16	44		227	09:33:53	227	10:18:05	788	660	691	
17	96		242	01:33:05	242	03:08:43	864	672	710	possible interface
18	167		272	09:07:29	273	11:54:41	800	677	712	possible interface

Table 1. The times of trailing edge interfaces for 18 streams identified in Ulysses data in 1992-3 are tabulated here. The duration is listed, as are the start and stop times. Also noted are the solar wind velocity at the interface and the minimum and maximum velocity on either side of the interface.

stream number	Entropy identification yr:day:hr:min	WS interface identification yr:day:hr:min	Comments
1	92:185:18:18 92:186:07:02 92:187:12:00*	92:186:10:00 92:185:18:00 92:187:14:00	
2	92:207:16:49	92:203:06:40 92:204:20:00 92:204:22:50	
3	92:232:21:39	92:230:18:00	
4	92:256:07:00 92:257:10:04*	92:257:09:42 92:257:20:15 92:258:01:50	
5	92:283:18:55	92:283:09:15	
6	92:309:09:00	92:309:00:20	
7	92:335:11:14	92:334:23:10	
8	92:363:08:07	92:363:07:30	
9	93:21:04:55	93:20:12:30 93:21:00:30 93:21:04:00	
10	93:52:03:16	93:52:04:00	not clear, data gap, may be multiple interfaces
11	93:73:09:00 93:76:03:40 93:78:19:39*	93:73:08:30	
12	93:98:06:00 93:104:05:04		also large entropy jump on days 96 and 97
13	93:130:07:00	93:128:20:15	
14	93:154	-	data gap from 154:04:00 - 154:20:00
15	93:181:10:00	93:181:10:40	
16	93:206:23:00	93:205:12:00	
17	93:234:22:00		

Table 2. The interface identified by the largest jump in entropy at the leading edge of these same stream is shown here in the first column. Also shown, for comparison are the identifications made by *Wimmer-Schweingruber* [1997].



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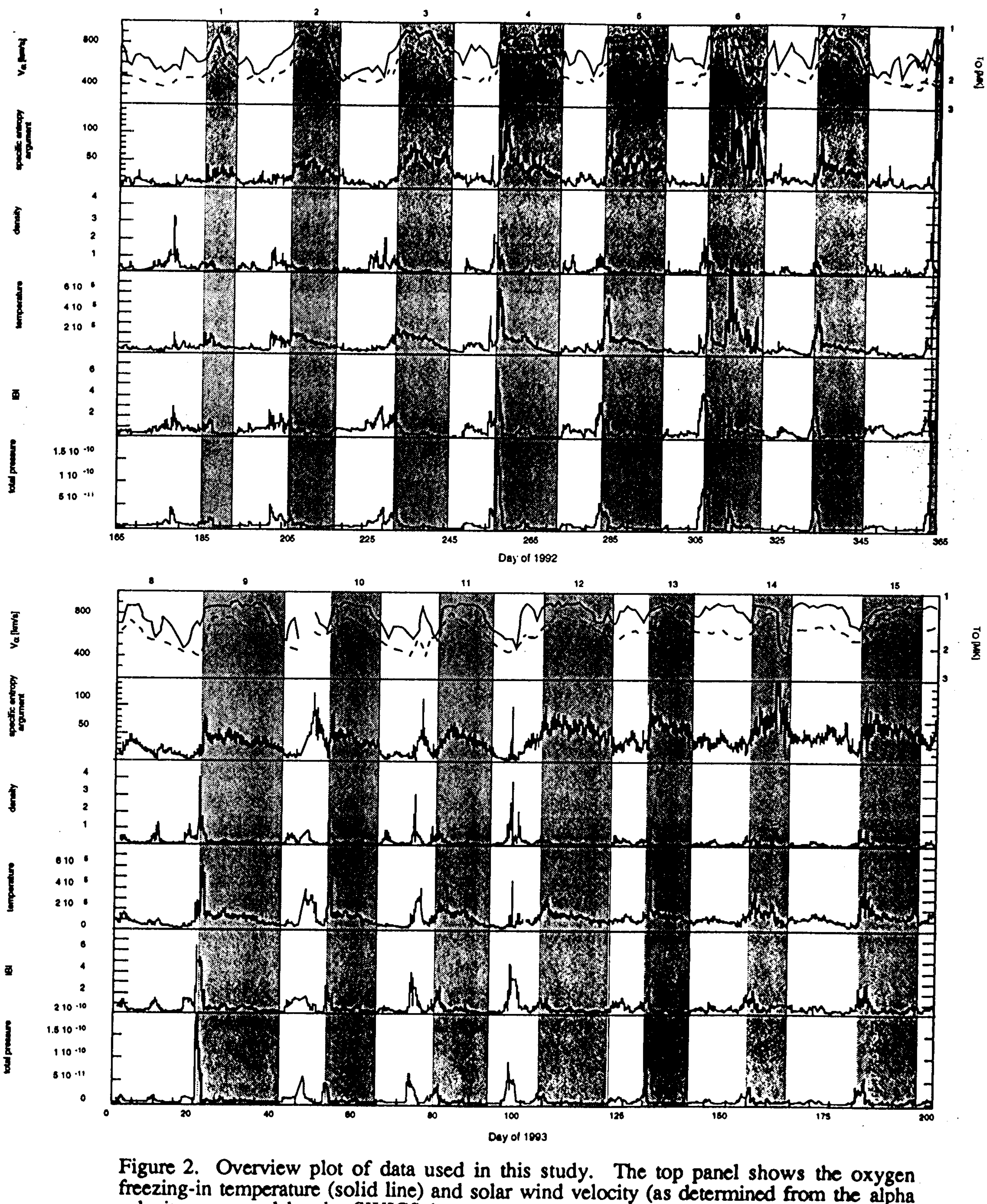

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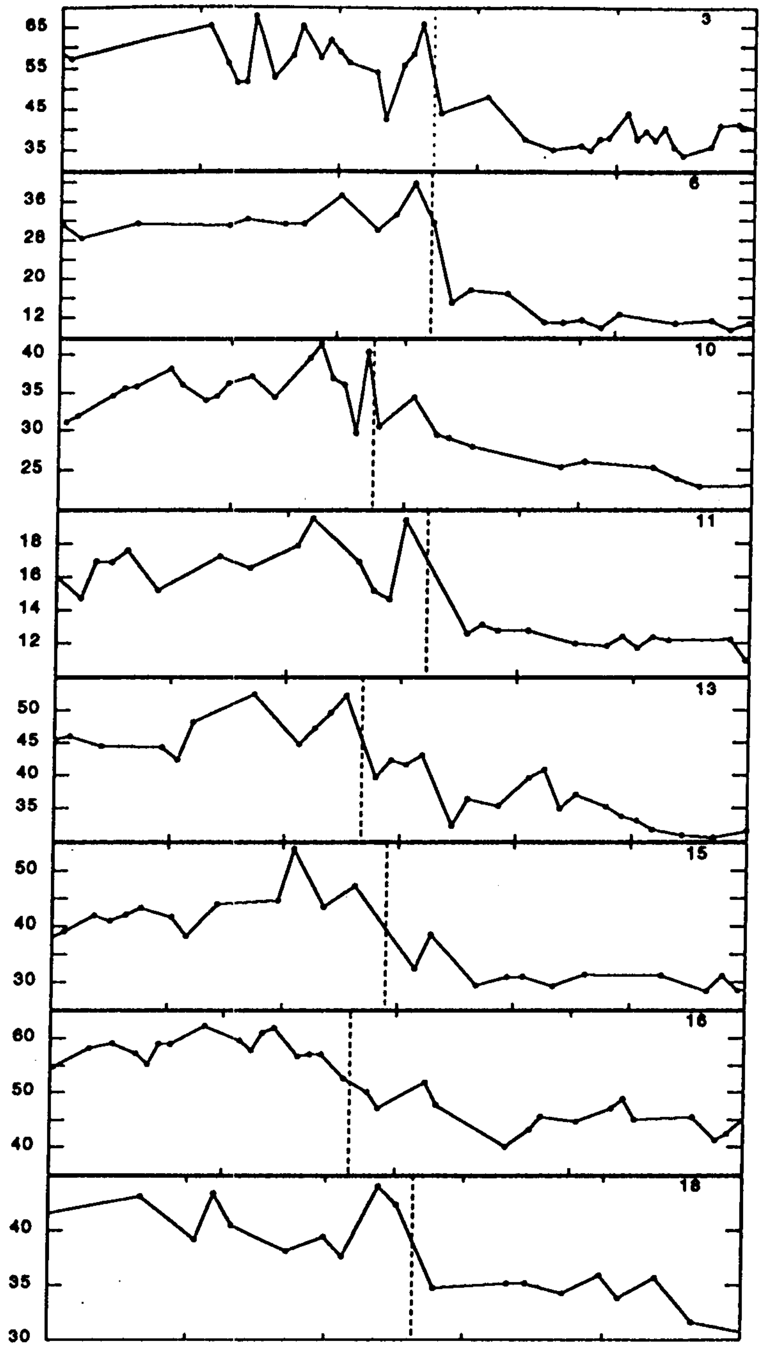

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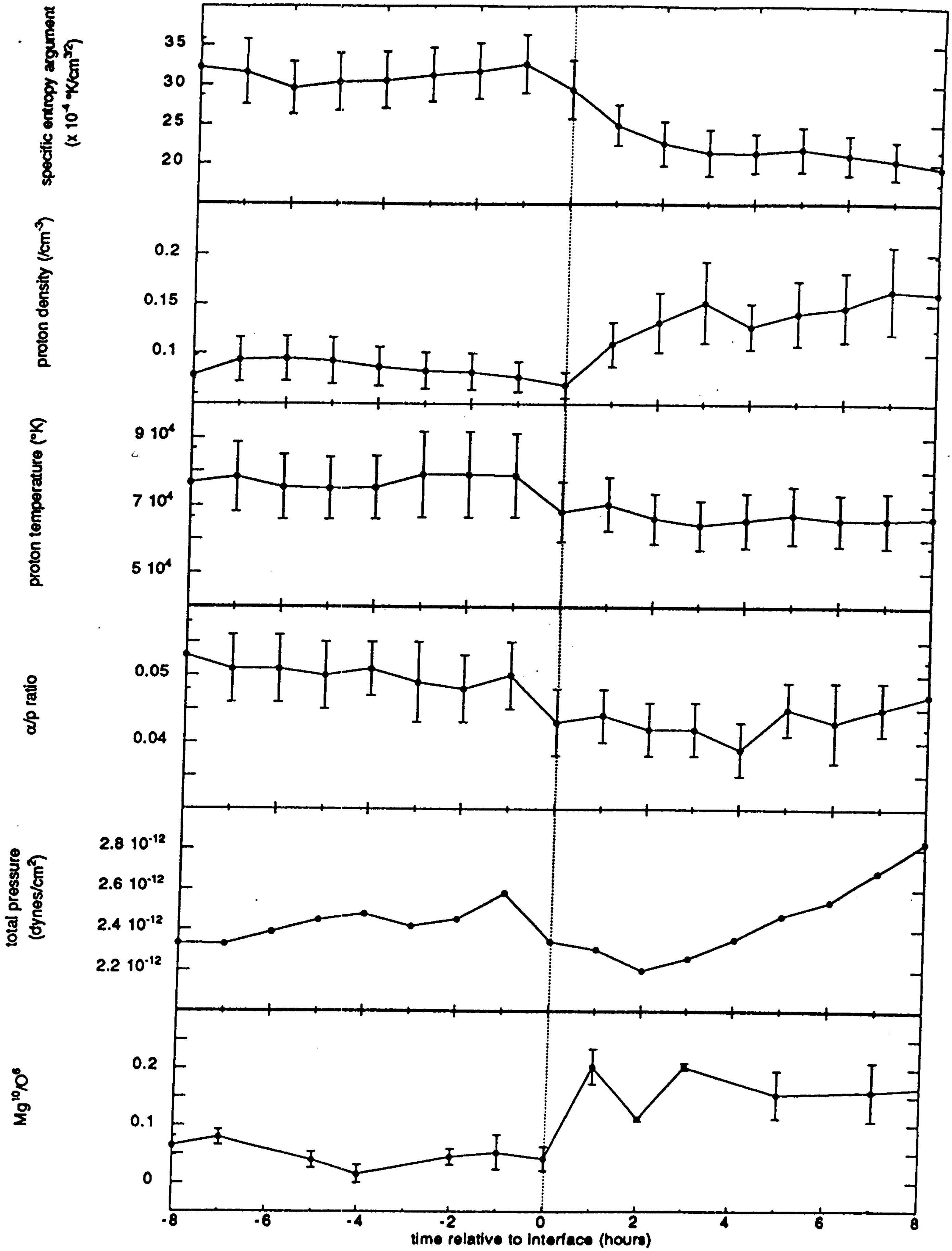

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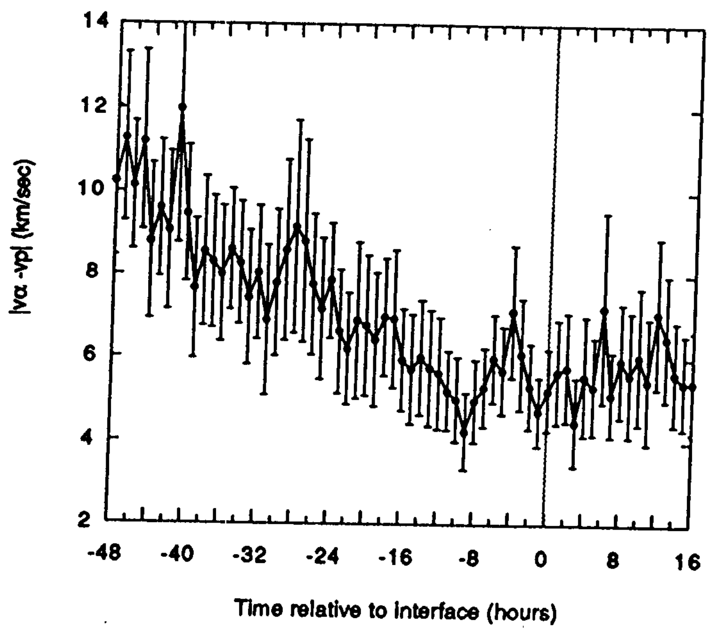

Figure 5. Superposed epoch analysis for the alpha proton velocity difference over an extended interval, 2 days prior to and one and a half days following the trailing interface.

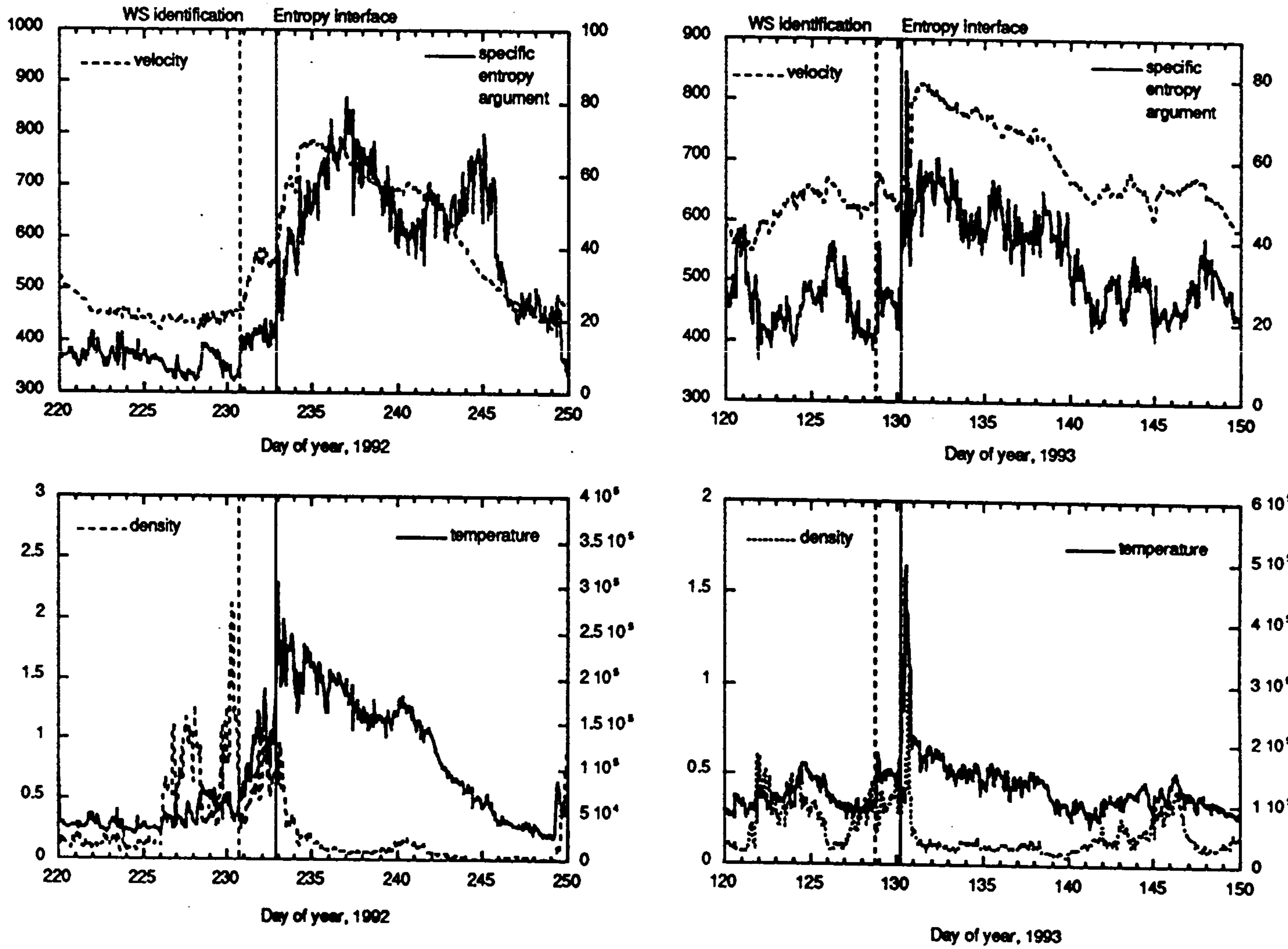

Figure 6. Two examples of leading edge interfaces in which discrepancies exist between the identifications of Wimmer-Schweingruber and those marked by the largest jump in specific entropy argument. The WS identification is marked by a dashed line and the entropy interface is marked with a solid line. The corresponding density and temperature profiles are shown in the bottom panels.